Interclonal and within-tree variation in wood properties of poplar clones

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Abstract: The wood basic density, cellulose content and fiber form were investigated for all sample trees at breast height (1.3 m) in seven poplar clones, and at 0 (butt), 5.6, 9.6, 13.6, 17.6, 19.6 and 21.6 m for clone Nanlin-95 and Nanlin-895, respectively, for providing information on variation patterns of wood density, fiber characteristics and holocellulose content within trees and among clones. The results showed that significant variations about wood density, cellulose content, fiber diameter and the ratio of fiber length to diameter existed among poplar clones examined. Variance analysis indicated that there were significant differences in wood basic density, fiber length, fiber diameter and cellulose content among the growth rings, which had an increasing tendency along the direction from pith to bark. The significant differences also existed in wood basic density, fiber length and fiber diameter at different tree height. The mean wood basic density had a general increase trend with increasing height of trees and the lowest was found at the base, while fiber length and fiber diameter had a general decline pattern with increasing height of trees and the biggest value was observed at the height of 5.6 m. Regression analysis indicated that the relationship between examined wood properties and growth ring number (cambial age), and the relationship between examined wood properties and tree height can be described by polynomial functions.

Keywords: Poplar clone; Wood basic density; Fiber characteristics; Cellulose content; Clonal variation; Within-tree variation
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Introduction

Poplars are interspersed primarily in temperate forests of the northern hemisphere. They are relatively short-lived, and fast-growing trees that can grow on marginal soils. Increasing demand for wood has prompted investigations into the potential of fast-growing species as raw material for various wood industries. Since the National Natural Forest Protection Program was announced by the central government in 1998, logging in natural stands has been banned in 18 provinces in China, while the national reforestation program has been intensified (Bao *et al.* 2001). As a result, plantations in China will play a critical role in meeting the nation's wood demand. Poplars can be used for different forms of processing in the timber industry and in the fiber industry as a source of energy (Gambles *et al.* 1984; Fang *et al.* 1999). Since some poplar clones were introduced to China in the 1970s, poplars have become the major tree species both in plantation forestry and agroforestry systems throughout the south temperate central area of China, an area of roughly 600 000 km^2 (Fang *et al.* 1999). Interest in short-rotation production of various poplar hybrids for fiber and veneer has accelerated greatly in central China and Jianghan plain during the past decades (Xu *et al.* 1997). However, little attention has been paid to the wood quality of poplar clones. China breeding program for poplar tree was, in the past, concentrated on selection for such features as growth rate, stem form and crown form. Recently there has been renewed interest in selection based on wood-quality criteria such as basic density, tracheid (fiber) length and chemical composition (Koubaa *et al.* 1998; Hernandez *et al.* 1998; Blankenhorn *et al.* 1985a; Blankenhorn *et al.* 1985b). Wood density and fiber characteristics are important to the pulp and paper industry and have been addressed by some researchers for poplar tree improvement program (Zobel 1976; Yanchuk *et al.* 1984; Beaudoin *et al.* 1992; Koubaa *et al.* 1998; Hernandez *et al.* 1998). It is possible that wood from some poplar hybrids with superior growth rates, improved form, adaptability and good fiber characteristics for pulp and paper may be less suitable for solid wood products. This means that to diversify wood utilization, poplar clones and hybrids should be selected for a variety of wood properties. Hence, the aims of this study were to provide information on variation patterns of wood density, fiber characteristics and holocellulose content within tree and among clones in south-central China.

Materials and methods

Materials

Discs were collected from 7 poplar clones, growing in two clonal trials in Hanyuan Forestry Farm, Baoing County,

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Jiangsu Province, China (33°08′N, 119°19′E). The seven poplar clones were as follows: clone I-69 (*Populus deltoids* Bartr. cv. 'Lux'), clone I-72 (*P.* ×*euramaricana* (Dode) Guinier cv. 'San Martino'), clone NI-80351, a hybrid of clone I-69 × clone I-63 (*P. deltoids* Bartr. cv. 'Havard'), and the other four clones (Nanlin-95, Nanlin-895, Nanlin-447 and Nanlin-1388), new hybrids of clone I-69 × clone I-45 (P. ×*euramaricana* (Dode) Guinier cv. 'I-45/51'). All the seven poplar clones are considered as veneer and ground pulp timber production in China.

Sampling

The selection of the sample tree was based on the mean DBH and the means height of total trees in the plots. DBH for all trees and the total height within 15% of the mean DBH in each plot were measured before sampling. The single tree with DBH of closest to the means of DBH and height at good form and vigour was selected for destructive sampling (Table 1). Two trees were sampled for each poplar clone and totally 14 trees were destructively sampled in the study.

Table 1. General characteristics of the poplar clone plantations in the study

Clones	Spacing /m	Stand age /a	Tree height /m	DBH /cm	Tree volume / m^3
NL-80351	4×5	12	22.8	22.5	0.3705
I-69	4×5	12	22.9	20.1	0.3097
I-72	4×5	12	22.9	21.4	0.3543
Nanlin-95	6×6	11	25.7	26.9	0.6275
Nanlin-447	6×6	11	27.0	30.2	0.8670
Nanlin-895	6×6	11	25.1	28.0	0.6618
Nanlin-1388	6×6	11	25.2	26.8	0.5197

Each sample tree was cut at ground level. The discs were collected from the beginning of butt at 1.3, 3.6, 5.6, 7.6, 9.6, 11.6, 13.6, 15.6, 17.6, 19.6, 21.6 m high. Growth increment was measured for each growth ring at the breast height (at 1.3 m). Samples of springwood and latewood were also taken from each of the growth rings on the discs at breast height. Not all the discs were sub-sampled for wood property measurement. The wood basic density, fiber characteristics and holocellulose content were measured at breast height for all sample trees, and the discs at 0 (butt), 5.6, 9.6, 13.6, 17.6, 19.6 and 21.6 m high for clone Nanlin-95 and Nanlin-895 were prepared for measuring characteristics of wood basic density and fiber.

Laboratory procedures and data analysis

A bark-to-bark strip of wood was cut across the diameter of each disc and strips were cut in a north-south direction. Each strip was first used for determining basic density, and then for measuring characteristics of fiber and holocellulose. Fiber length and fiber diameter were measured from maceration using image analysis system, and fifty measurements samples were taken for each parameter. Wood basic density on the oven-dry weight/green volume, was calculated according to the following formula (Cheng 1985):

$$D = 1 / [(W_1 / W_2) - 1] \tag{1}$$

where, D is Basic density, W_1 is saturated weight of the sample, W_2 is oven-dry weight of the sample.

Cellulose content was determined based on the national standard for chemical analysis (National Technical Monitoring Bureau 1981). Data from this study were analyzed using SAS software. Analysis of variance (ANOVA) was performed for determining wood properties. Duncan's multiple range tests was used when ANOVA results indicated that there were significant differences. The SAS statistical approaches were also used for fitting lines and curves by linear and non-linear methods.

Results and discussion

Interclonal variation in wood properties

The mean cellulose content, wood basic density, fiber length, fiber diameter and ratio of fiber length at diameter of breast height (1.3 m) from seven poplar clones are presented in Table 2. Duncan's mean separation letters are listed next to each mean value.

Table 2. Average value of seven poplar clones on holocellulose content, wood basic density and fiber traits at breast height

Poplar clones	Cellulose content (%)	Wood basic density /g·cm^3	Fiber length /μm	Fiber width /μm	Ratio of fiber length to diameter
I-69	51.08DCc	0.387BACba	1112.82A	25.97Aa	42.74BCb
I-72	50.17Dc	0.397BAba	1079.39A	24.09BCba	44.88BACba
NL-80351	50.46DCc	0.374Cb	1093.27A	24.11BCba	45.32BAba
Nanlin-95	54.89Aa	0.381BCba	1110.90A	23.35Cb	47.72Aa
Nanlin-447	53.41Bb	0.374Cb	1094.43A	25.55BAba	42.85BCb
Nanlin-895	53.32Bb	0.400Aa	1106.12A	24.27BCba	45.66BAba
Nanlin-1388	51.50Cc	0.385BACba	1091.25A	26.26Aa	41.50Cb
Mean value	52.12	0.386	1098.33	24.80	44.38

Notes: the same letter means no significantly different; a small letter represents at the 0.01 level; a capital letter represents at the 0.05 level.

The overall average cellulose content of the 7 poplar clones was 51.12%, ranging from 50.17% to 54.89%. The ranking of cellulose content by poplar clone is Nanlin-95 > Nanlin-447 > Nanlin-895 > Nanlin-1388 > I-69 > NL-80351 > I-72. Analysis of variance for the cellulose content showed that significant variation existed among seven poplar clones (alpha=0.01). The average cellulose content in this study for 7 clones agreed with the reported average values for 4 poplar clones by Cao *et al.* (1997) at the same stand age, while the average value was much higher than

the result from Fang *et al.* (1996) in poplar coppice system with 1-3 rotation lengths. Although Blankenhorn *et al.* (1985a) reported that holocellulose content for seven hybrid poplar clones ranged from 60% to 74%, Bao *et al.* (2001) indicated that the holocellulose content in sanbei poplar (*P. nigra* x *P. simonii* cv. 'Zhonglin Sanbei-1') was from 76.9% to 78.5%. It is reasonable to estimate that the cellulose contents in those poplar clones are similar to the results from our study. Compared to the content of 10-year-old eucalyptus species where the wood cellulose content ranged from 43% to 45% (Cotterill *et al.* 1997), the cellulose content in poplars was slight higher. The average basic density of the 7 poplar clones was 0.386 g/cm^3, ranging from 0.374 g/cm^3 to 0.400 g/cm^3. The difference was statistically significant among seven poplar clones (alpha=0.01). The basic densities in clone Nanlin-895 were 0.8%, 3.4%, 3.9%, 5.0%, 7.0% and 7.0% higher than these of I-72, I-69, Nanlin-1388, Nanlin-95, Nanlin-447 and NI-80351, respectively, and the highest value occurred in clone Nanlin-895. Compared to previous research results in poplars, the basic density from our study was little higher. Bendtsen and Senft (1986) indicated that the specific gravity of eastern cottonwood ranged from 0.330 to 0.396. Hernandez *et al.* (1998) reported that the overall average basic density of nine-year-old ten euramericana clones was 335 kg/m^3, which was lower than that of *P. deltoids* (352 kg/m^3) and *P. tremuloides* (374 kg/m^3). The high value in our study could be due to difference in the measurement methods of wood density. Reported wood basic densities of eucalyptus species or clones varied widely from 0.420 to 0.577 (Cotterill *et al.* 1997; Lima *et al.* 2000), which was much higher than that of the poplars.

The overall average fiber length of the seven poplar clones was 1098.33 μm at breast height, ranging from 1079.39 μm to 1112.82 μm, in agreement with the results reported from clones I-69, I-72, I-63 and I-214 (*P. ×euramaricana* (Dode) Guinier cv. 'I-214') by Cao *et al.* (1997) and similar to the reported average for ten euramericana clones (1.015 mm) by Koubaa *et al.* (1998). However, the fiber length of clone I-69 and clone NL-80351 from this study was much higher than that (0.74-0.85 mm) from poplar coppice system for the same poplar clones (Fang *et al.* 1996). It is suggested that rotation length may affect the fiber length significantly. The ANOVA indicated that non-significant difference in fiber length existed among the tested clones. The maximum average fiber length was found in clone I-69, and the minimum average fiber length was found in clone I-72. Compared to the reported average fiber length of eucalyptus species or clones (Cotterill *et al.* 1997; Muneri *et al.* 2001; Rao *et al.* 2002), the average fiber length of poplar clones from this study was higher.

The average fiber diameter of the seven clones ranged from 23 μm to 26 μm, while the ratio of fiber length to diameter ranged from 41 to 48. Variance analysis showed that there was significant difference both in fiber diameter and the ratio of fiber length to fiber diameter among seven poplar clones (alpha=0.01).

The most interest to the pulp and paper industry is those wood fiber morphology and wood chemistry properties that determine key paper qualities such as refinability, strength, opacity, porosity, and bulk. The high wood density is an important factor in its low wood consumption, which has become an increasingly critical factor to continued profitability of the pulp industry (Cotterill *et al.* 1997). High cellulose content in wood will obtain high pulp yield, and relatively long and thin wood fiber can improve the tensile strength and tear-strength of paper. From the view of growth rate, cellulose content, wood basic density and wood fiber morphology for clone Nalin-95 and clone Nalin-895 have much more potential of extension in south-central China as a raw material of pulp and paper industry.

Variation of wood properties from pith to bark

Wood basic density

The variation of wood basic density with cambial age for seven poplar clones was shown in Fig. 1. The average wood basic density at breast height (1.3 m) varied from 0.330 g/cm^3 to 0.421 g/cm^3 between growth rings with cambial age, which showed a pity-to-bark trend of increasing wood density, although this varied from clone to clone. Variance analysis showed that there were significant differences in wood basic density among the rings (alpha=0.01). The lowest wood basic density was observed in the first two growth rings from pith and increased from pith to bark, while the pith-to-bark trend leveled off around ring 6 from the pith where the mean basic density was over 0.390 g/cm^3. Regression analysis indicated that a polynomial function best described the relationship between wood basic density and cambial age, and the R^2 reached 0.94. There existed significant differences in wood basic density between springwood and latewood for poplar clones (alpha=0.01). The mean springwood basic density was 0.368 g/cm^3, while that of the latewood was 0.399 g/cm^3 (Fig. 2).

Hernandez *et al.* (1998) studied within-tree variation on increment cores of *P. ×euramaricana* clones, and found that wood density decreased slightly from the pith to the first third of the diameter, and then increased outwards. Trembling aspen (*P. tremuloides*) wood exhibits a similar pattern of variation (Yanchuk *et al.* 1983). Our research result suggests a positive effect of cambial age on basic density, in agreement with the result from Norway spruce (*Picea abies*), (Lindstrom 1996).

Fiber characteristics

The average fiber length at breast height ranged from 830 μm to 1270 μm between growth rings with cambial age, while the average fiber diameter varied from 23 μm to 26 μm (Figs.3 and 4). The effect of the position of annual rings from pith on fiber length was highly significant (alpha=0.01). The fiber length was initially quite short near the pith, then steadily increased. This showed a tendency to level off at the eighth annual ring. A similar pattern has frequently been

reported for poplars and their hybrids (Cheng *et al.* 1979; Yanchuk *et al.* 1984; Bendtsen *et al.* 1986; Sierra-Alvarez *et al.* 1995; Cao *et al.* 1997; Koubaa *et al* 1998). Fiber diameter increased with distance from the pith and significant difference in fiber diameter was found between the growth rings (alpha=0.05), which confirmed the results observed by Cao *et al.* (1997) in previous study on four poplar clones (I-69, I-63, I-72, and I-214). Similar results have been also reported by Taylor (1973) and Malan *et al.* (1987) on South African *Eucalyptus grandis*. Regression analysis indicated that a polynomial function best described the relationship between fiber characteristics and cambial age, and the R^2 reached 0.99 for fiber length and 0.94 for fiber diameter, respectively.

Cellulose content

The variation in cellulose content with cambial age for seven poplar clones was shown in Fig. 5. The average cellulose content at breast height varied from 48.0% to 54.6% between growth rings with cambial age, which showed a pity-to-bark trend of increasing cellulose content from clone to clone. Variance analysis showed that there were significant differences in wood basic density among the rings (alpha=0.01). The lowest wood basic density was observed in the first two growth rings from pith (below 50%) and increased from pith to bark, while the pith-to-bark trend leveled off around ring 7 from the pith where the mean cellulose content was about 53%, in agreement with the results reported by Cao *et al.* (1997) on four poplar clones. Regression analysis indicated that a polynomial function best described the relationship between cellulose content and cambial age, and the R^2 reached 0.97.

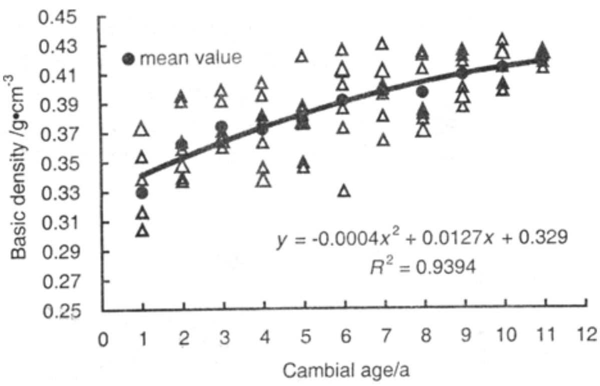

Fig. 1 Variation in wood basic density at breast height with cambial age for 7 poplar clones

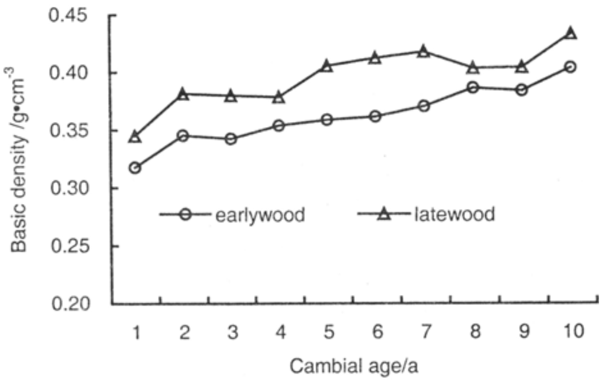

Fig. 2 Variation in mean wood basic density between springwood and latewood at breast height for 7 poplar

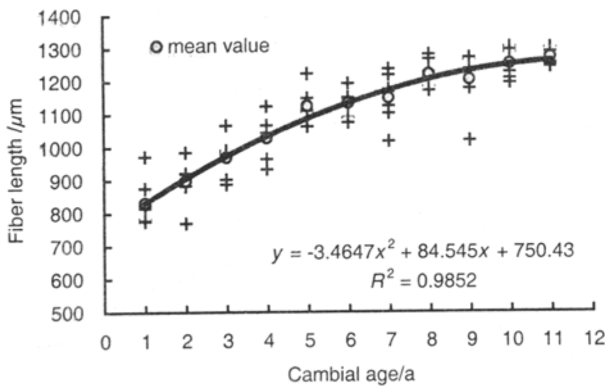

Fig. 3 Variation in fiber length at breast height with cambial age for 7 poplar clones clones

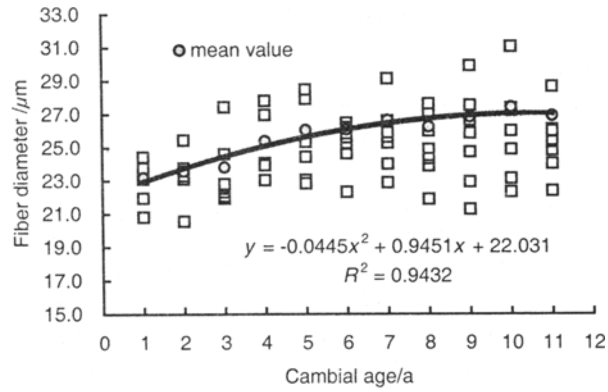

Fig. 4 Variation in fiber diameter at breast height with cambial age for 7 poplar clones

Variation in wood basic density and fiber characteristics at different tree height

Wood basic density

Wood basic density of two poplar clones (Nanlin-95 and Nanlin-895) varied from 0.37 g/cm^3 to 0.40 g/cm^3 in different tree heights, the lowest being found at the base (Fig.6), which showed a general increase trend in wood basic density with increasing height. In all discs, the mean wood

density of the two poplar clones also showed a consistent pith-to-bark trend of increasing wood density, in agreement with the trend of the disc at breast height. Regression analysis indicated that a polynomial function best described the relationship between wood basic density and tree height, and the R^2 reached 0.85.

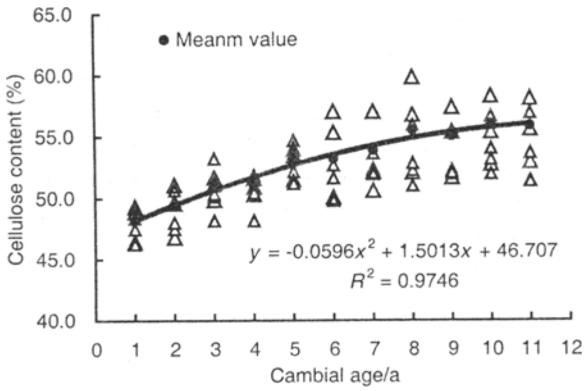

Fig. 5 Variation in holocellulose content at breast height with cambial age for7 poplar clones

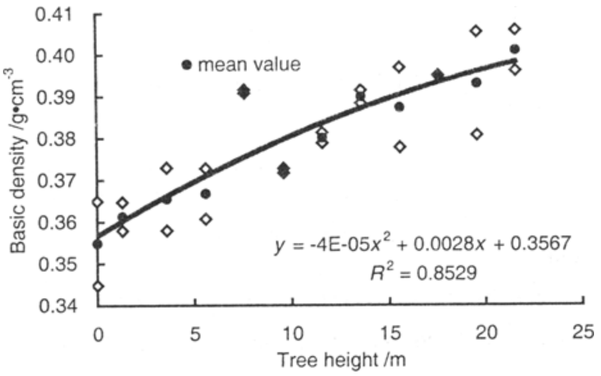

Fig. 6 Variation in wood basic density at different tree heights for 2 poplar clones (Nanlin-95 and Nanlin-895)

Fiber characteristics

The effect of tree height on the fiber length was significant (alpha=0.01). Mean fiber length of two poplar clones (Nanlin-95 and Nanlin-895) varied from 770 μm to 1055 μm at different tree heights. The fiber length initially increased slightly from the base of the tree, reaching the highest at the 5.6 m, and then plateaued before decreasing towards the apex (Fig.7). Regression analysis indicated that a polynomial function best described the relationship between fiber length and tree height, and the R^2 reached 0.95. A similar trend in fiber length variation was also reported by Koubaa *et al.* (1998) on poplar hybrid clones, and by Muneri and Raymond (2001) on *Eucalyptus globules* and *E. nitens*, while no definite trend from bottom to top within each tree was observed by Rao *et al.* (2002) on some clones of *E. tereticornis*.

Fiber diameter is significantly varied from bottom to top within trees (alpha=0.05). Mean fiber diameter of two poplar clones (Nanlin-95 and Nanlin-895) varied from 21 μm to 25 μm in different tree heights (Fig.8). Maximum average fiber diameter was found at the height of 5.6 m, and minimum average fiber diameter at 21.6 m. Variation pattern in fiber diameter with tree height was similar to that of the fiber length. Regression analysis indicated that a polynomial function best described the relationship between fiber length and tree height, and the R^2 was 0.89. Fiber diameter and fiber length were also positively correlated and the correlation was found to be highly significant (R = 0.73), in agreement with the reported results on clones of *E. tereticornis* (Rao *et al.* 2002).

Conclusions

Wood basic density, cellulose content, fiber length, fiber diameter and the ratio of fiber length to diameter in the poplar clones showed a clonal variation. There existed significant differences in wood basic density, cellulose content, fiber diameter and the ratio of fiber length to diameter among seven poplar clones except for fiber length. From the view of growth rate, cellulose content, wood basic density and wood fiber morphology for clone Nalin-95 and clone Nalin-895 may have much more potential of extension in south-central China as a raw material of pulp and paper industry.

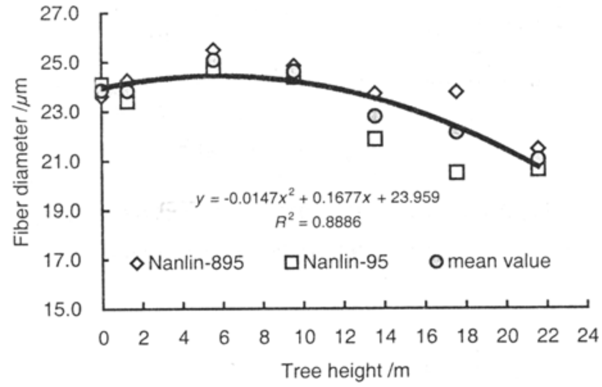

Fig. 7 Variation in fiber length at different tree heights for 2 poplar clones

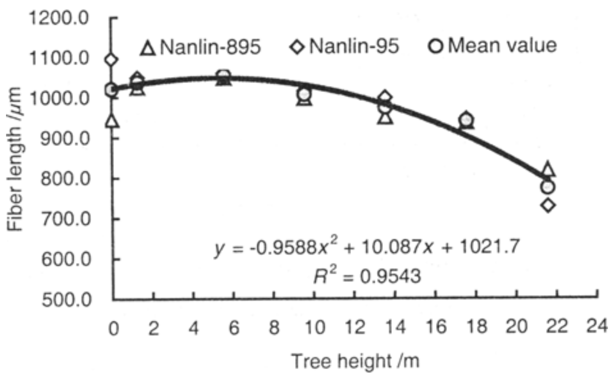

Fig. 8 Variation in fiber diameter at different tree heights for 2 poplar clones

Wood basic density, fiber characteristics and cellulose

content varied from pity to bark, which showed a consistent pity-to-bark trend of increasing in wood density, fiber length, fiber diameter and cellulose content. Variance analysis indicated that there were significant differences in wood basic density, fiber length, fiber diameter and cellulose content among the rings. Regression analysis indicated that a polynomial function could best describe the relationship between wood basic density, fiber characteristics, cellulose content and growth ring number (cambial age).

Wood basic density and fiber characteristics of two poplar clones (Nanlin-95 and Nanlin-895) varied with tree heights. The mean wood basic density showed a general increase trend with increasing height and the lowest was found at the base. The fiber length and fiber diameter showed a general decline pattern with increasing height and both the highest values were observed at the height of 5.6 m in all heights (discs). The mean wood basic density of the two poplar clones also showed a consistent pith-to-bark trend of increasing wood density. Variance analysis indicated that there were significant differences in wood basic density, fiber length and fiber diameter among the various positions of tree height. Regression analysis showed that the relationship between wood basic density, fiber length, fiber diameter and tree heights was best described by polynomial functions, although the applicability of this relationship to a wider sample of trees should be examined.

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